RF POWER AMPLIFIER AND METHODS FOR IMPROVING THE EFFICIENCY THEREOF

BACKGROUND OF THE INVENTION

A typical radio transmitter uses a radio frequency (RF) power amplifier to amplify outbound signals for transmission by an antenna. A linear power amplifier receives a signal at an input power and produces the signal at an output power, which is the input power amplified by a gain. The linear power amplifier is driven by a direct current (DC) input voltage, provided for example by a battery in the transmitter, and the efficiency of the power amplifier is given by the ratio of the output power to the DC input power. RF power amplifiers are generally designed to provide maximum efficiency at the maximal output power. When the power amplifier produces an output power that is less than the maximal output power, the efficiency of the power amplifier may be significantly reduced.

There are several situations where the output power of an RF transmitter needs to be less than the maximal output power ("power control"). For example, in amplitude modification (AM) radio transmission, the instantaneous output power is set according to the instantaneous strength of the modulating audio to be transmitted. In the case of battery-operated portable handsets such as cellular telephones and pagers, the power amplifier is one of the main current consumption elements, and power control is used in order to prolong the lifetime of the battery. Power control is also used to reduce interference between different calls in the same vicinity and to reduce the

radiation emitted by the handset. In fact, modern cellular systems allow handset transmission at low power for long periods of time.

However, since the efficiency of the power amplifier is significantly reduced when the power amplifier produces an output power that is less than the maximal output power, more battery power at lower output power is actually consumed. It would therefore be beneficial to improve the efficiency of the RF power amplifier at lower output powers without reducing the efficiency at the maximal output power.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood and appreciated more fully from the following detailed description taken in conjunction with the appended drawings in which:

Figs. 1A and 1B are a schematic illustration of an exemplary radio frequency (RF) transmitter including an exemplary power amplifier, according to an embodiment of the invention;

Fig. 2A is a graphical illustration of the efficiency η of the RF transmitter of Figs. 1A and 1B as a function of the normalized output power;

Fig. 2B is a graphical illustration of the efficiency η of the RF transmitter of Figs. 1A and 1B as a function of the normalized output power when the phase shifts have discrete values;

Fig. 3 is a schematic illustration of another exemplary RF transmitter including another exemplary power amplifier, according to an embodiment of the invention;

Fig. 4 is a schematic illustration of a further exemplary power amplifier, according to an embodiment of the invention; and

Fig. 5 is a graphical illustration of the efficiency η of the RF transmitter of Figs. 1A and 1B as a function of the normalized output power, when bias control is performed at two output powers, according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

Embodiments of the present invention are directed to a radio frequency (RF) power amplifier. Embodiments of the present invention are also directed to a method for controlling the output power of a radio frequency amplifier.

Up-conversion from baseband frequencies to radio frequencies involves an up-conversion chain, which includes a chain of amplifiers and preamplifiers interspersed with modulators, mixers and bandpass filters. Reference is now made to Figs. 1A and 1B, which are a schematic illustration of an exemplary radio frequency (RF) transmitter including an exemplary power amplifier, according to an embodiment of the present invention. A baseband modulation signal 100 may be provided to an intermediate frequency (IF) modulator 102. IF modulator 102 may receive an IF local oscillator (LO) signal from an IF local oscillator (LO) 104. IF modulator 102 may modulate the IF LO signal with baseband modulation signal 100, thus producing an IF modulated signal 106. IF modulated signal 106 may be provided to an IF amplifier 108, which may amplify it by a gain γ_{IF}, thus producing an amplified IF modulated signal 110. A mixer 112 may receive an RF LO signal from an RF local oscillator 114. Mixer 112 may mix the RF LO signal with signal 110, thus producing an RF signal 116. RF signal 116 may be filtered by a bandpass filter 118, and then provided to an RF preamplifier 120, which may amplify it by a gain γ_{RF} thus producing an RF signal 122. RF signal 122 may be provided to a power amplifier 124, which may amplify it to an output power for transmission by an antenna 126. Either IF amplifier 108 or RF preamplifier 120, or both, have a variable gain (γ_{IF} and/or γ_{RF}) that can be controlled by power amplifier

124 according to the desired value of the output power. The controller of th radio transmitter may provide the desired value of the output power to power amplifier 124, as indicated by arrow 127.

Power amplifier 124 is shown in detail in Fig. 1B. Power amplifier 124 comprises an outphasing system 128 with shunt reactance and a logic controller 130. The input to outphasing system 128 is RF signal 122. The amplitude of RF signal 122 may be determined by many factors, among them the modulation and the gain of IF amplifier 108 and RF preamplifier 120.

Outphasing systems with shunt reactance (commonly known as Chireix outphasing systems) are known in the art. An example is described in F. Raab, "Efficiency of Outphasing RF Power-Amplifier Systems", IEEE Transactions on Communications, vol. COM-33, No. 10, Oct. 1985. The Chireix outphasing system was designed in 1935 to improve the efficiency and linearity of AM broadcast transmitters. It comprises a transmission-line-coupler with shunt reactance. An outphasing system with shunt reactance achieves maximal efficiency for two values of the output power.

Outphasing system 128 comprises two branch amplifiers 132 and 134 connected in parallel and a splitter 136 for splitting RF signal 122, so that a signal with half the input power is provided to branch amplifier 132 and a signal with half the input power is provided to branch amplifier 134. Branch amplifiers 132 and 134 are driven by a DC input voltage V_{DC}. Outphasing system 128 also comprises phase shifters 138 and 140 for modifying the phase of RF signal 122 provided to branch amplifiers 132 and 134, respectively. Outphasing system 128 may include shunt reactance elements 142 and 144 at the output of branch amplifiers 132 and 134, respectively. B_S is the shunt reactance of

element 142 and $-B_S$ is the shunt reactance of element 144. Through proper selection of the shunt reactance B_S, the efficiency may be maximized at a specific output power. The efficiency of a specific output power may be improved by the adjusting of the shunt reactance B_S.

Outphasing system 128 may also comprise a transmission-line-coupler 146 for combining the outputs of branch amplifiers 132 and 134. Transmission-line-coupler 146 comprises two transmission lines 148 and 150, each of which serves as an impedance inverter connected to antenna 126 so that the sum of the branch currents goes through the load. Other combiner schemes yielding the same perfomance could be implemented instead, namely Hybrid BALUN or center tap inductor.

Logic controller 130 controls the output power of power amplifier 124 according to the desired value of the output power. Logic controller 130 controls the output power of the power amplifier by utilizing two methods of power control. For a first range of output powers, for example 15 dB, logic controller 130 performs outphasing. Logic controller 130 may vary the phase of outphasing system 128 in order that outphasing system 128 provides antenna 126 with a signal at an output power according to the desired value. For a second range of output powers, logic controller 130 varies the amplitude of RF signal 122, which is the input to outphasing system 128. The operation of logic controller 130 is better understood if reference is made additionally to Figs. 2A and 2B.

Fig. 2A is a graphical illustration of the efficiency B_S of the RF transmitter of Figs. 1A and 1B as a function of the normalized output power. The outphasing system with shunt reactance has a peak efficiency at P1, and a

peak efficiency at P2. When the desired output power is at or greater than a threshold, namely P1, logic controller 130 performs outphasing, setting the phase ϕ_m so that outphasing system 128 applies $+\phi_m$ to phase shifter 138 and $-\phi_m$ to phase shifter 140, thus producing an output power according to the desired value. It can be seen that when the output power is at or greater than P1, the efficiency of the RF transmitter of Figs. 1A and 1B is the same as that of a pure Chireix outphasing system.

For the range of output powers below threshold P1, logic controller 130 keeps the phase ϕ_m constant at ϕ_{m-MAX} and reduces the gain (γ_{IF} and/or γ_{RF}) of IF amplifier 108 or RF preamplifier 120 or both, thus reducing the amplitude of RF signal 122, which is the input to outphasing system 128. It can be seen that at the range of output powers below threshold P1, the efficiency of the RF transmitter of Figs. 1A and 1B is significantly improved with respect to both the class-B power amplifiers and a pure Chireix outphasing system.

It will be appreciated by persons of ordinary skill in the art that IF amplifier 108 could be replaced by a series of IF amplifiers, at least one of which has variable gain which is controlled by logic controller 130 when the desired output power is lower than P1. Similarly, it will be appreciated that RF preamplifier 120 could be replaced by a series of RF preamplifiers, at least one of which has variable gain which is controlled by logic controller 130 when the desired output power is lower than P1. In general, any serial combination of IF amplifiers prior to mixer 112 and any serial combination of RF preamplifiers prior to power amplifier 124 could be used, provided that at least one of the IF amplifiers and RF preamplifiers has variable gain which is controlled by logic controller 130 when the desired output power is lower than P1.

In another example of the present invention, the phase shifts $+\phi_m$ and $-\phi_m$ provided by the logic controller to the phase shifters do not vary continuously between ϕ_{m-MIN} and ϕ_{m-MAX}, but set the phase to a value from a collection of discrete phase values. Fig. 2B is a graphical illustration of the efficiency η of the RF transmitter of Figs. 1A and 1B as a function of the normalized output power when the phase shifts have discrete values.

Reference is now made to Fig. 3, which is a schematic illustration of another exemplary RF transmitter including an exemplary power amplifier, according to an embodiment of the present invention. A baseband modulation signal 300 may be provided to an RF modulator 313. RF modulator 313 may receive an RF LO signal from an RF local oscillator 314. RF modulator 313 may modulate the RF LO signal with baseband modulation signal 300, thus producing an RF signal 316. RF signal 316 may be filtered by a bandpass filter 318, and then may be provided to a chain of at least one RF preamplifier 320, which may amplify it by a gain γ_{RF} thus producing an RF signal 322. RF signal 322 may be provided to a power amplifier 324, which may amplify it to an output power for transmission by an antenna 326. At least one of the RF preamplifiers 320 may have a variable gain (γ_{RF}) that is controlled by power amplifier 324 according to the desired value of the output power. The controller of the radio transmitter may provide the desired value of the output power to power amplifier 324, as indicated by arrow 327.

Power amplifier 324 may comprise an outphasing system 328 with shunt reactance and a logic controller 330. The input to outphasing system 328 is RF signal 322. The amplitude of RF signal 322 is determined by many factors, among them the modulation and the gain of RF preamplifier 320.

Outphasing system 328 may be the same as or similar to outphasing system 128 of Fig. 1B and will not be described further.

Logic controll r 330 may control the output power of power amplifier 324 according to the desired value of the output power. Referring again briefly to Fig. 2A, when the desired value of the output power is at or greater than a threshold, namely P1, logic controller 330 performs outphasing, setting the phase ϕ_m so that outphasing system 328 provides antenna 126 with a signal at an output power according to the desired value. It can be seen that when the output power is at or greater than P1, the efficiency of the RF transmitter of Fig. 3 is the same as that of a pure Chireix outphasing system. For desired output powers lower than P1, logic controller 330 may keep the phase ϕ_m constant at ϕ_{m-MAX} and varies the gain (γ_{RF}) of at least one of the variable gain RF preamplifiers 320, thus reducing the amplitude of RF signal 322, which is the input to outphasing system 328. It can be seen that at output powers lower than threshold P1, the efficiency of the RF transmitter of Fig. 3 is is significantly improved with respect to both the class-B power amplifiers and a pure Chireix outphasing system.

According to another aspect of the present invention, the logic controller sets the gain of at least one of the IF amplifiers and the RF preamplifiers even when the desired value of the output power is at or above threshold P1 in order to improve the efficiency of the outphasing system 128 and/or 328.

Reference is now made to Fig. 4, which is a schematic illustration of a further exemplary power amplifier, according to an embodiment of the invention. A power amplifier 424 receives an input RF signal 422 and amplifies

it for transmission by an antenna 426. Power amplifier 424 comprises an outphasing system 428 with shunt reactance and a logic controller 430.

Outphasing system 428 comprises two branch amplifiers 432 and 434 connected in parallel and a splitter 436 for splitting RF signal 422, so that a signal with half the input power is provided to branch amplifier 432 and a signal with half the input power is provided to branch amplifier 434. Branch amplifiers 132 and 134 are driven by a DC input voltage V_{DC}. Outphasing system 428 also comprises phase shifters 438 and 440 for modifying the phase of RF signal 422 provided to branch amplifiers 432 and 434, respectively. Outphasing system 428 includes shunt reactance elements 442 and 444 at the output of branch amplifiers 432 and 434, respectively. B_S is the shunt reactance of element 442 and $-B_S$ is the shunt reactance of element 444. Through proper selection of the shunt reactance B_S, the efficiency may be improved at a specific output power.

Outphasing system 428 also comprises a transmission-line-coupler 446 for combining the outputs of branch amplifiers 432 and 434. Transmission-line-coupler 446 comprises two transmission lines 448 and 450, each of which serves as an impedance inverter connected to antenna 426 so that the sum of the branch currents goes through the load. Other combiner schemes yielding the same performance could be implemented instead, namely Hybrid BALUN or center tap inductor.

Outphasing system 428 is similar to outphasing system 128 of Fig. 1B, with a difference that outphasing system 428 further comprises at least one RF preamplifier 400 between splitter 436 and phase shifter 438 and at least one RF preamplifier 402 between splitter 436 and phase shifter 440. At least one of

RF preamplifier 400 may have a variable gain $\gamma_{RF}^{(1)}$ and at least one of RF preamplifier 402 has variable gain $\gamma_{RF}^{(2)}$. Logic controller 430 sets the gain for each of RF preamplifier 400 and RF preamplifier 402 separately in order to improve the efficiency of outphasing system 428.

Power amplifiers may have a bias current in order to preserve its linearity. The consumption of bias current may decrease the efficiency of the power amplifier. At high output powers, this decrease in efficiency may be relatively unimportant. However, at low output powers, the loss in efficiency is significant. Bias control is the act of adjusting the bias current in order to increase the efficiency of the power amplifier, and is known in the art.

According to another aspect of the present invention, the internal bias current of a power amplifier comprising an outphasing system with shunt reactance may be reduced at low output powers, where the power amplifier may be more linear. This may affect the linearity of the power amplifier, but it may also improve the efficiency.

Reference is now made to Fig. 5, which is a graphical illustration of the efficiency η of the RF transmitter of Figs. 1A and 1B as a function of the normalized output power, when bias control is performed. Bias control is performed at two output powers, indicated by peaks 500 and 502. By comparing the graph of Fig. 5 with that of Fig. 2A, it can be seen that bias control may improve the efficiency of the RF transmitter of Figs. 1A and 1B at low output powers.

As explained hereinabove, the branch amplifiers of an outphasing system with shunt reactance are driven by a direct current (DC) input voltage, provided for example by a battery in the transmitter. It is known in the art that at

low output powers, reducing the DC input voltage improves the efficiency of the branch amplifiers without significantly damaging the linearity. By reducing the supply voltage of the branch amplifiers 132 and 134 of Fig. 1B and 432 and 434 of Fig. 4, the efficiency of the outphasing system is improved at the output power range below P1.

According to another aspect of the present invention, the DC input voltage of the branch amplifiers for an outphasing system with shunt reactance is reduced at the output power range below P1.

It will be appreciated by persons of ordinary skill in the art that the present invention is not limited by what has been particularly shown and described herein above. Rather the scope of the invention is defined by the claims that follow: